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# Thermo-Optic Effects and Opto-Electrical Bias in an Electro-Optic Modulation System

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## Abstract

In this work, for an electro-optic (EO) crystal, various thermo-optic (TO) and relevant temperature-dependence parameters are defined, presented and studied in the framework of a transverse and a longitudinal EO-modulation system. This study has been based on the concept of the so-called opto-electrical bias (φ) applied to the system. For both of the above EO-modulation systems a set of four original equations has been extracted and is investigated as regards each of the more important TO or temperature coefficients. Using these equations, for these parameters the role of the transverse configuration is examined in comparison with its corresponding longitudinal configuration. A calculation of uncertaintities in the determination of the principal temperature coefficients concludes the paper.

**Keywords:** Electro-optic and Thermo-optic effects.

## 1. Introduction

It is known that electro-optic (EO) crystals used in an intensity-modulation (IM) electro-optic system exhibit an EO response that may be strongly affected by thermo-optic (TO) and relevant temperature effects [1, 2, 3]. In the entire EO modulation system, these effects can be examined via their influence on the position and thermal stability of the operating point over the system's characteristic (transfer) curve [3]. Under these conditions, the concept and the role of the applied optical and electrical bias may be important [4]. The present work presents a novel consideration of the electro-optic and thermo-optic effects which are made on the basis of the combined opto-electrical (optical and electrical) bias and the corresponding thermal stability along the aforementioned transfer curve [3]. In this framework, our interest has been focused the thermo-optic behaviour of an EO modulator crystal as it is expressed by the influence of temperature T on crystal's optical or electro-optical quantities such as the refractive indices, $n_0$ and $n_e$, the effective EO coefficient r, the spontaneous birefringence $\Delta n^{(0)}$, the half-wave voltage $V_\pi$, the optical phase retardation Γ, and the intensity-modulation (IM) depth m of the entire EO-modulation system. After stating the appropriate definitions of the corresponding thermo-optic and temperature coefficients, we have derived and presented useful original equations connecting these parameters when either a transverse or a longitudinal configuration is used in the IM EO-modulation system. Then we present investigations of these equations as regards the above parameters and calculations of the uncertaintities in the determination of temperature coefficients for the effective EO coefficient r, the half-wave voltage $V_\pi$, and the IM depth m.

## 2. Typical transverse and longitudinal configurations of the system

EO systems used for optical intensity modulation (IM) or for EO and/or TO measurements are often based on Sénarmont-type arrangements such as those shown in Fig. 1 [3, 5]. As seen, the EO crystal sample S is placed between a polarizer P and a quarter-wave plate Q, with its neutral axes oriented at $45^0$ to the axes of the crystal and the polarizer. This quarter-wave plate is backed by a rotatable analyzer A, positioned at an azimuthal angle $\beta$, which allows to measure the changes of the optical phase retardation $\Gamma$ introduced by the crystal sample.

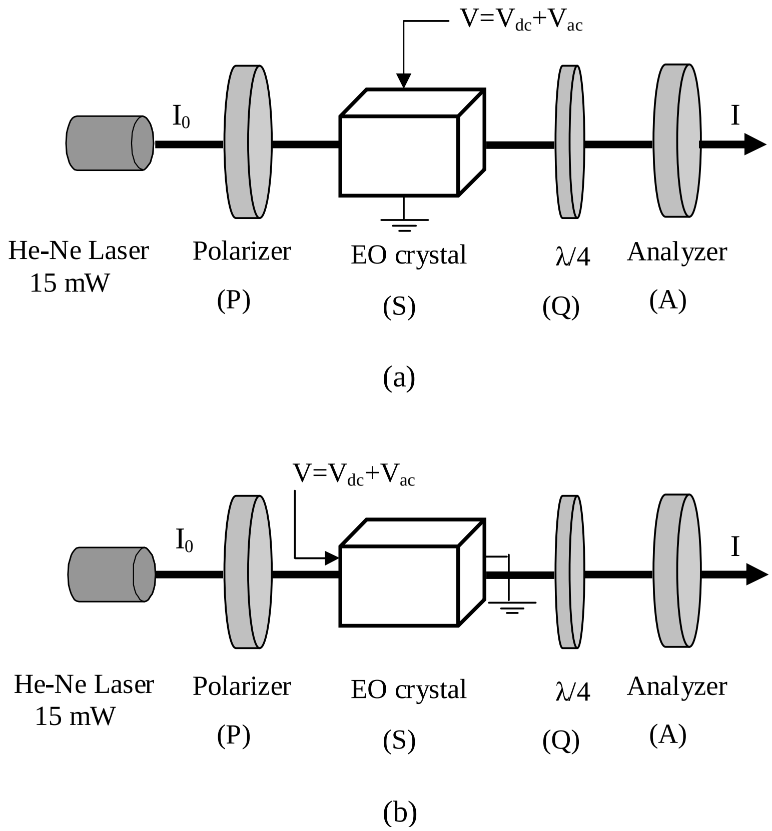


**Figure 1: Electro-optic modulation system (Sénarmont setup): (a) Transverse EO-modulation configuration and (b) Longitudinal EO-modulation configuration.**

In general, for systems of the above kind, the transfer function of the transmitted laser light intensity I can be put in the form $I=f(\varphi)$, where $\varphi$ is a quantity called the opto-electrical bias of the system and defined by [3]

$$\varphi = \Gamma - 2\beta \,. \qquad \ldots\ (1)$$

More precisely, for systems such as those shown in Fig. 1 the transfer function becomes [3, 6]

$$T = \frac{I_0 T_0}{2}\left(1-\sin\varphi\right) \qquad \ldots\ (2)$$

where $I_0$ denotes the intensity of laser light incident to the input polarizer and the transmission factor $T_0$ stands to take into account the losses of light due to reflections and absorptions inside the system.

In what follows, the crystal sample is assumed linearly electro-optic in the sense that, in the presence of an applied electric field E=V/s (where V is the applied voltage and s the electrode spacing), a field-induced birefringence [7, 8]

$$\Delta n_E = \frac{1}{2} n^3 r E = \frac{n^3 r}{2s} V \qquad \ldots(3)$$

is superimposed on the natural birefringence $\Delta n(0)$, with r representing the effective EO coefficient and n the active refractive index of the sample. Applying to the last of Eq. (3) the well-known formula [3]

$$\Gamma = \left(\frac{2\pi L}{\lambda_0}\right)\Delta n , \quad \text{…. (4)}$$

where L is the length of the crystal (along the laser beam) and $\lambda_0$ the wavelength of the laser beam in a vacuum and equal to (632.8 nm), one obtains for the field-induced optical phase retardation the expression

$$\Gamma_E = \left(\frac{\pi}{\lambda_0}\right)Ln^3rE = \pi\left(\frac{V}{V_\pi}\right), \quad \text{…. (5)}$$

where

$$V_\pi = \frac{\lambda_0}{n^3r}\left(\frac{s}{L}\right) \quad \text{…… (6)}$$

is the half-wave voltage of the crystal sample for the configuration under consideration.

In the case of a transverse EO modulator, the applied electric field E is directed perpendicular to the laser beam, as shown in Fig. 1a, and therefore the electrode spacing s will be equal to the crystal thickness d. Consequently, as a result of Eq. (6), for this configuration the half-wave voltage will be given by the relationship

$$V_\pi = \left(\frac{\lambda_0}{n^3r}\right)\left(\frac{d}{L}\right), \quad \text{…. (7)}$$

hence it will be proportional to the dimension ratio d/L. Accordingly, in the transverse EO-modulation system under consideration the half-wave voltage of the sample could be considerably reduced if d is taken significantly smaller than L and, moreover, it would be affected by anisotropies in the thermal expansion of the crystal.

By contrast, in the case of a longitudinal EO-modulator, in which the applied electric field is directed parallel to the laser beam, as shown in Fig. 1b, the electrode spacing s is equal to L and therefore Eq. (6) yields for the half-wave voltage the formula

$$V_\pi = \frac{\lambda_0}{n^3r} \quad \text{…. (8)}$$

Accordingly, for the longitudinal configuration under consideration the half-wave voltage of the crystal is independent on its dimensions, and their thermal expansions, and depends only on the thermo-optic effects affecting the refractive index and the EO coefficient of the crystal.

When either of the entire systems of Fig. 1 is used for (IM) electro-optic modulation, the I-φ curve, representing the transfer function according to Eq. (2), can be taken as the characteristic curve of the system (Fig. 2). As it can be seen from Eqs. (1)-(5), the position of the quiescent point on this characteristic curve is controlled by the opto-electrical bias φ and can be established by adjusting either the azimuthal angle β of the analyzer (optical bias) or/and the applied electric dc voltage $V=V_{dc}$ (electrical bias) which controls the static retardation $\overline{\Gamma} = \Gamma^{(0)} + \Gamma_{dc}$, where $\Gamma^{(0)}$ is the natural phase retardation and $\Gamma_{dc}=\pi(V_{dc}/V_\pi)$ is the dc-bias phase retardation. By virtue of Eq. (1), the total opto-electrical bias will be given by the expression

$$\overline{\varphi} = \overline{\Gamma} - 2\beta = \Gamma^{(0)} + \pi\left(V_{dc}/V_\pi\right) - 2\beta \; . \quad \text{…. (9)}$$

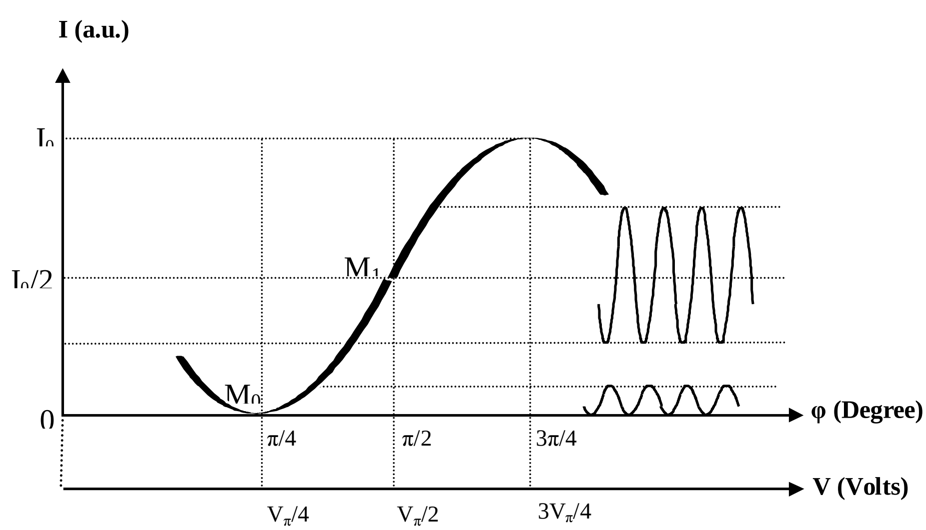


**Figure 2: Transfer function I(φ) or I(V) through Sénarmont setup**

It is known that one of the more important quiescent points along the I-φ characteristic curve is the minimum-transmission point, $M_0$, for which the derivative of f(φ) is zero. On the assumption of validity of Eq. (2), along with Eq. (9), it is easily proven that this point corresponds to a total opto-electrical bias $\overline{\varphi} = \varphi_0 = (1/2 + 2k)\pi|\; k = 0, \pm 1, ...$ and is attained when the condition $\Gamma^{(0)} + (V_{dc}/V_\pi - 1/2 - k)\pi = \beta$ is met. This point is also called the double-frequency point, because if an ac field of frequency ω is applied to the crystal a clear signal modulated at a frequency 2ω appears at the demodulated output [6]. The double-frequency point can be used to measure the half-wave voltage $V_\pi$ and the effective EO coefficient r by means of a FDEOM method using the system of Fig. 1 [9, 10].

Another important quiescent point is the middle point $M_1$ corresponding to the midpoint intensity $I=I_0/2$ of the transfer function (Fig. 2). This point is also called the maximum-linearity point, because if an ac field of frequency ω is applied to the crystal a clear signal modulated at the same frequency, ω, appears at the demodulated output [6]. On the assumption of Eq. (2), along with Eq. (9), it is easily proven that the maximum-linearity point corresponds to a total opto-electrical bias $\overline{\varphi} = \varphi_1 = k\pi|\; k = 0, \pm 1, ...$ and is attained when the condition $\Gamma^{(0)} + (V_{dc}/V_\pi)\pi = 2\beta$ is met.

## 3. Relationships between TO parameters of EO interest

In an EO-modulation system, a number of TO parameters exist which refer to the temperature dependence of useful quantities interconnected in the framework of the system. To define these parameters, we have adopted the expressions p=du/dT and

$$q = \left(\frac{1}{u}\right)\left(\frac{du}{dT}\right) \quad \text{..... (10)}$$

for the TO coefficient and for the corresponding temperature coefficient, respectively, of a temperature dependent quantity u [3]. On the other hand, as Γ depends on various EO and TO parameters the thermal stability of the opto-electrical bias $\overline{\varphi} = \overline{\Gamma} - 2\beta$ will depend on the values of these parameters.

For the case of the typical Sénarmont-type transverse EO- modulation system, it has been proven that the following set of equations is valid for the EO and TO parameters in the operating point of the system [3]:

$$\rho = \frac{1}{r}\left(\frac{dr}{dT}\right) = -(\delta + 3\beta_e) + (\alpha_d - \alpha_L) \quad (10a)$$

$$n_1 n_2 (\beta_2 - \beta_1) = \overline{n}\,\Delta n^{(0)}(\mu_\Delta - \overline{\mu}) \quad (10b)$$

$$\kappa = \frac{d\overline{\Gamma}}{dT} = \Gamma^{(0)}(\mu_\Delta + \alpha_L) - \pi\delta\left(\frac{V_{dc}}{V_\pi}\right) \quad (10c)$$

$$\xi_m = \frac{1}{m}\left(\frac{dm}{dT}\right) = (\rho + 3\beta_e) - (\alpha_d - \alpha_L) \quad (10d)$$

In the above equations, the parameters ρ, δ, $\mu_\Delta$, and $\xi_m$ are the temperature coefficients for the effective EO coefficient r, the half-wave voltage $V_\pi$, the spontaneous birefringence $\Delta n^{(0)}$, and the IM depth m, respectively, defined by the expressions

$$\delta = \frac{1}{V_\pi}\left(\frac{dV_\pi}{dT}\right), \quad \mu\Delta = \frac{1}{\Delta n^{(0)}}\left(\frac{d\Delta n^{(0)}}{dT}\right), \quad (11)$$

where $dV_\pi/dT$ and $d\Delta n^{(0)}/dT$ are the thermo-optic coefficients for $V_\pi$ and $\Delta n^{(0)}$, respectively. As to the temperature coefficients $\alpha_L$ and $\alpha_d$ for the crystal length L and the crystal thickness d, respectively, they are given by

$$\alpha_L = \frac{1}{L}\left(\frac{dL}{dT}\right) \quad , \quad \alpha_d = \frac{1}{d}\left(\frac{dd}{dT}\right), ... \quad (12)$$

where dL/dT and dd/dT are the thermal expansion coefficients of the crystal along the directions L and d, respectively. Also, the temperature coefficients of the refractive indices $n_1=n_0$ and $n_2=n_e$, respectively, are defined by the expressions

$$\beta_1 = \beta_0 = \frac{1}{n_0}\left(\frac{dn_0}{dT}\right) \quad , \quad \beta_2 = \beta_e = \frac{1}{n_e}\left(\frac{dn_e}{dT}\right), \quad ..(13)$$

where $dn_0/dT$ and $dn_e/dT$ represent the corresponding thermo-optic coefficients. Lastly, $\overline{n} = (1/2)(n_1 + n_2)$ is the mean refractive index and κ represents the thermo-optic coefficient $d\overline{\Gamma}/dT$ of the static phase retardation $\overline{\Gamma}$.

For the case of the corresponding longitudinal EO-modulation system (using the same components), in which Eq. (8) holds instead of Eq. (7), we have extracted an original equations by means of a similar procedure that the above equations become

$$\rho=\frac{1}{r}\left(\frac{dr}{dT}\right)=-(\delta+3\beta_0) \quad \text{… (14a)}$$

$$n_1 n_2(\beta_2-\beta_1)=\bar{n}\,\Delta n^{(0)}\left(\mu_\Delta-\bar{\mu}\right) \quad \text{… (14b)}$$

$$\kappa=\frac{d\bar{\Gamma}}{dT}=\Gamma^{(0)}(\mu_\Delta+\alpha_L)-\pi\delta\left(\frac{V_{dc}}{V_\pi}\right) \quad \text{…(14c)}$$

$$\xi_m=\frac{1}{m}\left(\frac{dm}{dT}\right)=\rho+3\beta_0 \quad \text{… (14d)}$$

It is of note that, as regards the above thermo-optic or temperature coefficients of the crystal's refractive indices can be related to the thermo-optic deformation of the index ellipsoid (without field) as follows:

The anisotropy of thermo-optic effect, when refers to the refractive indices of a crystal, can be expressed by means of a 3x3 symmetric tensor [$k_{ij}$], we shall call the thermo-optic tensor, with components defined by the equation [11]

$$\Delta a_{ij}=k_{ij}\,\Delta T\Big|_{i,j=1,2,3} \quad \text{…(15)}$$

Where $\Delta T$ is the rise in temperature and $\Delta a_{ij}$ denote the corresponding changes in the components of the index tensor $a_{ij}$, which represent the coefficients of the equation to the optical index ellipsoid with respect to a system of orthogonal coordinate axes OX, OY, OZ.

In calculations, it is convenient to choose the principal axes, OX, OY, OZ of the index ellipsoid as axes of coordinates. For the higher symmetry crystals, precisely for those belonging to the cubic, hexagonal, trigonal, tetragonal and orthorhombic classes, these axes will coincide with the crystallographic axes and for $i\neq j$ it will hold $k_{ij}=0$, hence $\Delta a_{ij}$ $(i\neq j)=0$.

Accordingly, the effect of temperature would be to alter the magnitude of the principal axes of the index ellipsoid without any change in their orientation [11].

As a result, in the above crystal classes, it is possible and advisable to take the principal axes OX, OY, OZ as a temperature-independent system of coordinate axes, in which case the equation of the index ellipsoid becomes

$$a_{11}X^2+a_{22}Y^2+a_{33}Z^2=1 \quad \text{…(16)}$$

Moreover, without loss of generality, we may choose the direction OZ to be along the direction of propagation Os (Fig. 1). Then, by virtue of the well-known property of the index ellipsoid, at a given temperature T the two waves propagating as a result of birefringence along OZ will have refractive indices $n_1$ and $n_2$ equal to the principal radii of the central elliptic section of the ellipsoid perpendicular to OZ, hence obtained by putting Z=0 in Eq. 16. This leads to an ellipse in the XY plane with equation

$$\frac{X^2}{n_1^2}+\frac{Y^2}{n_2^2}=1 \quad \text{… (17)}$$

where

$$n_1=1/\sqrt{a_{11}},\quad n_2=1/\sqrt{a_{22}} \quad \text{… (18)}$$

Obviously, if OY is an optic axis, we shall have $n_1=n_o$ and $n_2=n_e$, where $n_o$ is the ordinary and $n_e$ the extraordinary refractive index of the crystal at temperature T.

By repeating the Eq. (18) for another temperature $T'=T+\Delta T$ it is easily deduced that, for the same direction of propagation Os, the refractive indices $n_1$ and $n_2$ will acquire new values $n'_1$ and $n'_2$, respectively, given by

$$n'_1=1/\sqrt{a'_{11}},\; n'_2=1/\sqrt{a'_{22}} \quad \text{… (19)}$$

where, on the basis of Eqs. 16 and 19, we shall have

$$a'_{11}=\left(1/n_1^2\right)+k_{11}\Delta T,\; a'_{22}=\left(1/n_2^2\right)+k_{22}\Delta T \quad \text{… (20)}$$

Using Eqs. (19) into Eqs. (20) and taking into account the approximation $(1+\chi)^\nu\approx1+\nu\chi\big|_{\chi<<1}$, we obtain for the birefringence along OZ the expression

$$\Delta n'=n'_2-n'_1=n_2\left(1+n_2^2k_{22}\Delta T\right)^{-1/2}-n_1\left(1+n_1^2k_{11}\Delta T\right)^{-1/2}=\Delta n-\frac{1}{2}\left(n_2^3k_{22}-n_1^3k_{11}\right)\Delta t \quad (21)$$

provided that

$$k_{11}<<1/n_1^2,\; k_{22}<<1/n_2^2$$

Which holds satisfactorily in practice, at least for symmetries of orthorhombic or higher, because then we have $k_{ii}=-\left(2/n_i^3\right)\left(dn_i/dT\right)$ with $dn_i/dT$ being of the order of $10^{-5}$°C$^{-1}$ [11]. It is to be emphasized that, as seen from the above sets of equations, Eqs. (10b) and (14b), which refer to the difference ($\beta_2$-$\beta_1$), and (10c) and (14c), which refer to the thermo-optic coefficient $\kappa$ of $\bar{\Gamma}$, are the same in the transverse and the longitudinal EO system. On the other hand, Eqs. (10a) and (14a), which refer to the temperature coefficient $\rho$, and Eqs. (10d) and (14d), which refer to the temperature coefficient $\xi_m$, differ by the thermal expansion term ($\alpha_d$-$\alpha_L$), which is absent in a longitudinal EO-modulation system. This fact may be advantageous for such a longitudinal system if the thermal expansion contribution is high in the corresponding transverse EO-modulation system.

## 4. Investigation and discussion

In what follows, working on the basis of Eqs. (10a)-(10d) and (14a)-(14d) which hold for the two configurations illustrated in Fig. 1, we shall first compare the principal thermo-optic or temperature parameters referring to a transverse EO-modulation system with those of its homologous longitudinal EO-modulation system.

We first consider the temperature coefficient $\rho$ of the crystal's EO coefficient r and the temperature coefficient $\xi_m$ of the modulation depth m, as they are ruled by Eqs. (10a), (10d) and (14a), (14d). For these parameters, one can discriminate three cases as follows.

In the first case, the thermal expansion is isotropic, hence $\alpha_d=\alpha_L$. Then, as seen from the above equations, the temperature coefficients $\rho$ and $\xi_m$ will be the same for both (transverse and longitudinal) EO-modulation configurations.

The second case occurs when the thermal expansion is anisotropic, with $\alpha_d>\alpha_L$. Then, from the above equations it is deduced that $\rho_{trans}>\rho_{long}$ and $\xi_{m,trans}>\xi_{m,long}$. This means that, as regards the thermal stability of r and m, the transverse EO-modulation system will then be worse than its homologous longitudinal EO-modulation system.

The third case takes place also when the thermal expansion is anisotropic, but with $\alpha_d<\alpha_L$. Then, from the above equations it is deduced that $\rho_{trans}<\rho_{long}$ and $\xi_{m,trans}<\xi_{m,long}$. This means that, as regards the thermal stability of r and m, the transverse EO-modulation system will then be better than its homologous longitudinal EO-modulation system.

Besides, as seen from Eqs. (10b), (10c) and (14b), (14c), the difference $\beta_2$-$\beta_1$ of temperature coefficients for the birefringence refractive indices and the thermo-optic coefficient $\kappa$ of the static phase retardation will be ruled by equations which are the same in both transverse and longitudinal EO-modulation systems.

Moreover, from either of Eqs. (10b) and (14b) we observe that, if $\Delta n^{(0)}=0$ (i.e., the crystal is isotropic or the propagation is along an optic axis), we shall have $\beta_1=\beta_2$. Consequently, two equal birefringence refractive indices will have also equal temperature coefficients. On the other hand, from Eqs. (10c) and (14c) we deduce that the thermo-optic coefficient $\kappa$ be zero when $\Gamma^{(0)}[\mu_\Delta+\alpha_L]=\pi\delta[V_{dc}/V_\pi]$. Consequently, under this condition, the static phase retardation $\overline{\Gamma}$ will become thermally insensitive.

It is finally of note that the first set of the above equations (Eqs. 10a-d) has been already used elsewhere by the authors to experimentally determined various TO coefficients of $LiTaO_3$ in the case of a transverse EO configuration [3].

## 5. Uncertainties in the determination of temperature coefficients

We now assume that, for a quantity u, a temperature coefficient q is directly determined on the basis of its definition formula, introduced by Eq. (10), which can be rewritten as

$$q=\left(\frac{1}{u}\right)\left(\frac{du}{dT}\right)\cong\left(\frac{1}{u}\right)\left(\frac{\Delta u}{\Delta T}\right), \qquad \ldots(22)$$

where $\Delta u$ is the variation of u measured for a variation $\Delta T$ in temperature T.

In this case, by applying in Eq. (22) the known law of propagation of errors we obtain for the relative error $\delta q/q$ the expression

$$\frac{\delta q}{q}=\frac{\delta u}{u}+\frac{\delta(\Delta u)}{\Delta u}+\frac{\delta(\Delta T)}{\Delta T} \qquad \ldots(23)$$

From this equation, using again Eq. (22), it is easily found that the corresponding uncertaintity in the value of q will be given as a function of q by

$$\delta q=\left[\frac{\delta u}{u}+\frac{\delta(\Delta T)}{\Delta T}\right]q+\frac{1}{u}\frac{\delta(\Delta u)}{\Delta T}. \quad \ldots(24)$$

If we apply the above equations for the temperature coefficient $\rho=(1/r)(\Delta r/\Delta T)$ of r we obtain for the corresponding uncertaintity the equation

$$\delta\rho=\left[\frac{\delta r}{r}+\frac{\delta(\Delta T)}{\Delta T}\right]\rho+\frac{1}{r}\frac{\delta(\Delta r)}{\Delta T}. \qquad \ldots(25)$$

Similarly, it is easily proven that the uncertaintity $\delta\mu_\Delta$ associated with the determination of $\mu_\Delta$ by its definition (see Eq. 11) will be given by the equation

$$\delta\mu_\Delta=\left[\frac{\delta(\Delta n^{(0)})}{\Delta n^{(0)}}+\frac{\delta(\Delta T)}{\Delta T}\right]\mu_\Delta+\frac{1}{\Delta n^{(0)}}\frac{\delta(\Delta\Delta n^{(0)})}{\Delta T}. \quad \ldots(26)$$

Finally, as regards the determination of the temperature coefficient $\xi_m=(1/m)(\Delta m/\Delta T)$ of the

IM depth m, the corresponding uncertaintity $\delta\xi_m$ is found to be ruled by the equation

$$\delta\xi_m = \left[\frac{\delta m}{m} + \frac{\delta(\Delta T)}{\Delta T}\right] m + \frac{1}{m}\frac{\delta(\Delta m)}{\Delta T} \text{ . ... (27)}$$

The above equations allow to calculate the uncertainties in the determination of the temperature dependent quantities $\rho$, $\mu_\Delta$, and $\xi_m$ when the relative errors appearing in the second member of equations are known or can be estimated.

## 6. Summary and conclusion

The first part of the present work has been initiated by introducing the concept of opto-electrical bias $\varphi$ in an EO-modulation system and has been continued by studying the corresponding thermal instability, expressed by various thermo-optic (TO) or temperature-dependence parameters. The study of parameters has shown that, in typical EO-modulation systems, various TO and temperature coefficients (referring to EO coefficient, birefringence, half-wave voltage, etc.) may play a significant role in the TO behaviour. In this study, it has been proven that the utilization of a transverse or a longitudinal configuration in the system may more or less affect the above parameters and modify the thermal stability of the EO crystal and the entire system as well. In the present work, we have derived a number of basic equations with which one can investigate the effect of temperature on the TO and other temperature-dependence parameters in both transverse and longitudinal EO-modulation systems. A comparison between these two configurations as regards the thermo-optic behaviour of the EO crystal and the entire system has been also effected. Finally, calculations of uncertaintities and relative errors are made and presented in case the temperature- dependence parameters are determined on the basis of their definitions.

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## الملخص:

في هذا العمل, لبلورات الكهروضوئية, متغيرات ثرموضوئية وبرامترات إعتماد درجة الحرارة قد عرفت, قدمت ودرست في نظام التضمين الكهروضوئي المستعرض والطولي. هذه الدراسة اعتمدت على أساس الانحياز الألكتروضوئي المسلط على النظام. لكلا نظامي التضمين الكهروضوئي أعلاه, أربع معادلات أصلية أستحدثت وفحصت كل واحدة منها لكثير من معاملات درجة الحرارة والثرموضوئي. باستخدام هذه المعادلات, للبرامترات أعلاه, الترتيب المستعرض أختبر بالمقارنة مع الترتيب الطولي المرافق له. أخيرا, حساب عدم الدقة في قياس معاملات درجة الحرارة ثم مناقشتها في هذا البحث.